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Comparison of Bergeron and frequency-dependent cable models for the simulation of electromagnetic transients

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***Abstract*—The simulation of electromagnetic transients involving underground cables is very time consuming, when compared with simulations involving overhead lines, and Bergeron models are often used instead of the more accurate frequency-dependent models, in order to reduce the simulation time.**

This paper analyses the simulation errors of different Bergeron models to a reference frequency-dependent model for a 150kV cable. The simulations consider flat and trefoil installation, both-ends bonding and cross-bonding, ideal voltage source and modelling of the area around the cable. The Bergeron model is simulated for three different target frequencies: transient's resonance frequency, 50Hz and an in-between frequency.

The results are analysed theoretically using modal propagation theory and the error is quantified for the case under examination. It is concluded that for a realistic case, which requires the modelling of the area around the cable being energised, the Bergeron model has a small error if tuned for the right frequency.

***Index Terms*—Electromagnetic Transients; Simulation and Modelling; HVAC cables; Bergeron Models; Frequency-dependent models**

I. INTRODUCTION

The simulation of electromagnetic transients like switching or lightning in transmission networks with HVAC cables can be a very time consuming task, both due to the need of modelling the minor-sections of cross-bonded cables, if present, and to the higher computational requirements of the existing frequency-dependent (FD) cable models, when compared with FD overhead-line (OHL) models. For this reason, the use of the faster and more stable Schnyder-Bergeron models (normally, just called Bergeron models), instead of FD-models, is commonly performed at industry for a first approximation of the results; moreover, these models tend to overestimate the overvoltage [1], which can be seen as a safety margin, being the FD models used only in cases where a high accuracy is required. Typically, the waveforms obtained using the two models are similar in the first instants after switching, with the differences becoming bigger with time. Frequently, one limits the analysis of transient's waveforms to the first peak, as this peak corresponds normally, but not always, to the maximum magnitude, with one big exception being temporary overvoltage that have a longer duration and are often result of resonances between the energised element and the network. As the differences for this first peak are normally small, the use of the Bergeron model is seen as acceptable.

Recommendations on the minimum requirements for the modelling of HVAC cables for different transient phenomena are given in [1], with generic guidelines for the simulation of electromagnetic transients being given in [2] and [3], but without a quantification of the error introduced when using Bergeron models, which will vary in function of the transient phenomena being simulated and system parameters.

This paper intends to research in more detail the differences observed when using Bergeron models and FD-models for simulations with HVAC cables. It is relevant to assess and quantify in more detail the error existing when using Bergeron models instead of FD-models, for different cases. This paper limits the analysis to switching in cross-bonded cables and both-ends bonded cables, because of space constrains. The modelling of the adjacent areas with different models is also considered, as the modelling depth influences the simulation results, because of the reflections occurring in the neighbour elements [4]. Future work will analyse the simulation of lightning in hybrid cable-OHL lines and temporary overvoltage in cable-based networks.

Another important topic is the specification of the target frequency of a Bergeron cable model. This travelling wave model is accurate to one frequency, contrary to FD-model that is accurate for different frequencies up to approximately 100 kHz. As a result, one should try to tune the Bergeron models to the frequency of interest, per example the main frequency associated to a switching transient. A sensitivity analysis of the error introduced by an inaccurate tuning is performed in this paper.

The two simulation models are not explained in detail in this paper and the readers can refer to [5] and [6] for a description of the Bergeron model and FD-model, respectively.

II. CABLE DESCRIPTION

The demonstrations made along the paper consider an 800mm2, 150kV (170kV) cable. Figure 1 shows a cross-section of one phase of the cable. The switching is always made at peak voltage, for maximum overvoltage, and the length of the cable is 10km. Only one phase is energised (synchronised switching). One of the outside phases is energised for flat formation.

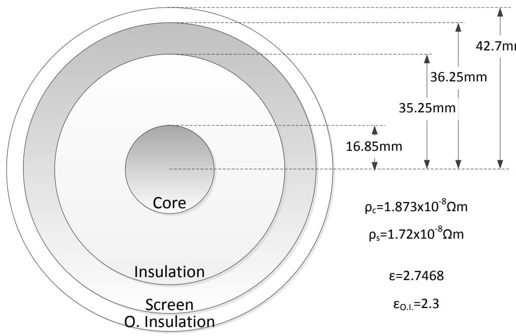

Figure 1 – Cable cross-section

Both flat and trefoil formation are consider. The former has the cables installed at 1m depth and with 1m separation, whereas the latter as the top phase at 1m depth and no distance between phases. The earth resistivity is 100Ω.m.

III. Ideal Systems Simulations

The first simulations consider the cable connected to an ideal voltage source, meaning that the voltage at the sending end of the cable is always purely sinusoidal. A consequence of using an ideal source is that the peak voltages are maximum and higher than in real system of equal nominal voltage. Another consequence is that the frequency of the transient is the maximum possible; in other words, the use of a Thévenin equivalent would lead to lower transient's frequencies. The modelling of the network up to two busbars behind the node of interest is recommended for the study of electromagnetic transients [2] and such modelling approach results in transient frequencies similar to those obtained with an ideal source, for strong networks. Therefore, an ideal voltage source is used in the first part of this paper.

A. *Simulation results*

Figure 2 shows the voltage at the end of a cable installed in flat formation and bonded at both-ends. Figure 3 shows the same cable, but with cross-bonding (1 major-section). Figure 4 and Figure 5 repeat the previous simulations for a cable installed in trefoil formation.

Four different models are used: A FD-model (reference waveform) and three Bergeron models: at 50Hz (steady-state frequency), at 4800Hz (approximation of the transient's main frequency) and at 500Hz.

The transient's target frequency can be obtained of several ways without having to do simulations. References [7] and [8] give examples on how to estimate this frequency. A more empirical approach possible with many software packages is to draw the cable using the respective geometric data and use the software to obtain the propagation times of the different coaxial modes. The transient's main frequency can then be calculated by considering the transient's period equal to 4τ (T=4τ), where τ is the travelling time of the coaxial modes from sending to receiving end. The transient's main frequency is the inverse to T.

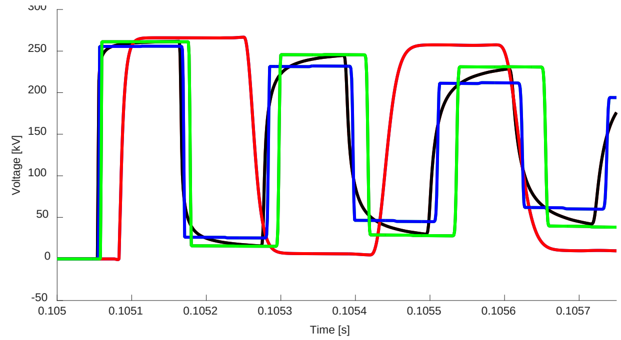

Figure 2 – Voltage at the end of the cable, both-ends bonding and flat installation, during energisation. Black: FD-model; Red: Bergeron-50Hz; Green: Bergeron-500Hz; Blue: Bergeron-4800Hz

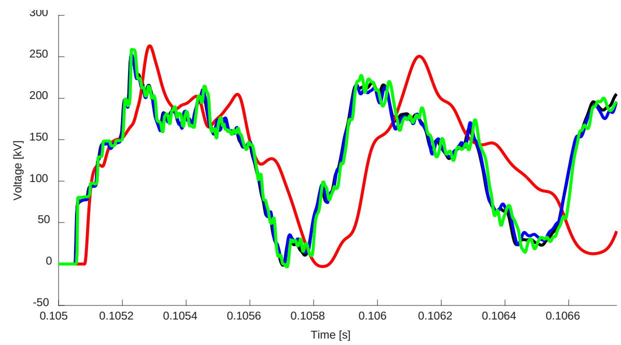

Figure 3 – Voltage at the end of the cable, 1 major cross-section and flat installation, during energisation. Black: FD-model; Red: Bergeron-50Hz; Green: Bergeron-500Hz; Blue: Bergeron-4800Hz

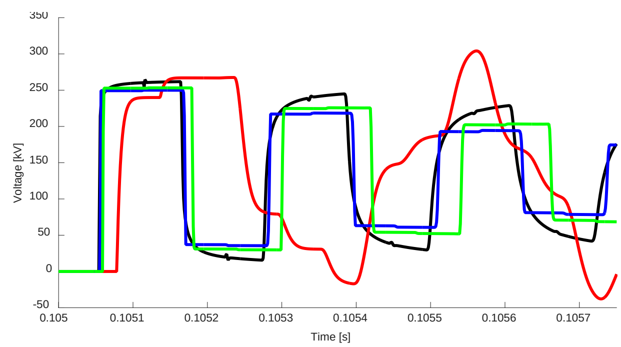

Figure 4 – Voltage at the end of the cable, both-ends bonding and trefoil installation, during energisation. Black: FD-model; Red: Bergeron-50Hz; Green: Bergeron-500Hz; Blue: Bergeron-4800Hz

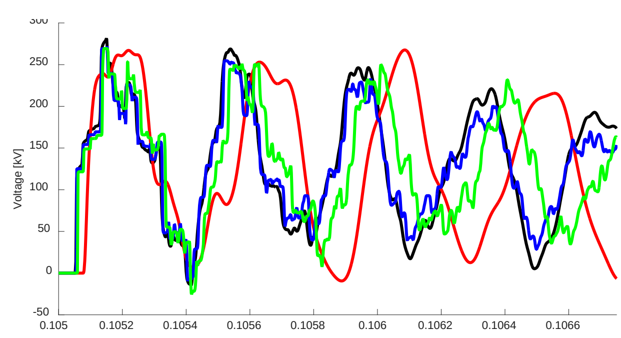

Figure 5 – Voltage at the end of the cable, 1 major cross-section and trefoil installation, during energisation. Black: FD-model; Red: Bergeron-50Hz; Green: Bergeron-500Hz; Blue: Bergeron-4800Hz

B. Analysis of the results

The differences in the waveforms caused by changes in the bonding configuration are not explained thoroughly in this paper. The readers can refer to [4] and [9] for more details.

The core and screen waves of three-phase single-core cables can be divided, using a transformation matrix, into six decoupled propagation modes, also called the modal domain: 3 coaxial modes, 2 intersheath modes and 1 ground mode [10].

The modal theory can be seen as analogous to symmetrical components to overhead lines. More precisely, symmetrical components are a particular case of modal domain for three phases. These modes have different propagation velocities and attenuations, both frequency dependent. Figure 6 shows the propagation speed and Figure 7 the attenuation of the six modes for the cable simulated in this paper for both trefoil and flat formations.

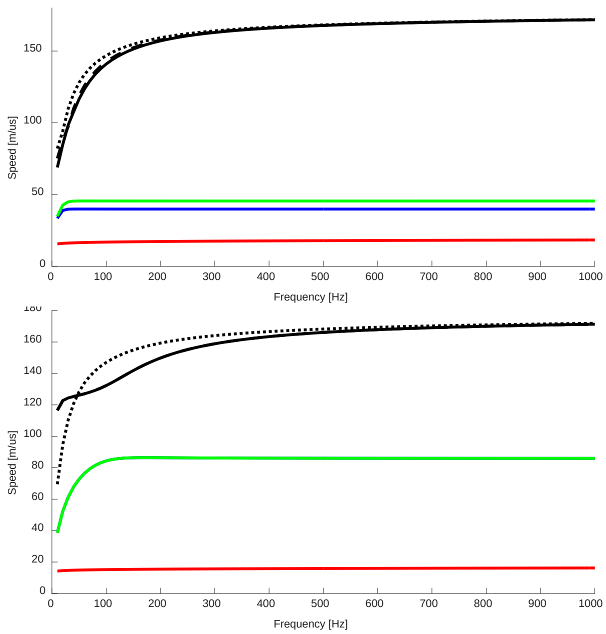

Figure 6 – Propagation speed of the different modes. Top: Flat formation; Bottom: Trefoil formation; Black: Coaxial modes; Green and blue: Intersheath modes; Red: Ground mode

The figures show that the velocity of the modes increases as the frequency increases only at lower frequencies. The speed of the ground and intersheath modes stabilises for low frequencies, below 150Hz for these particular cases, whereas the coaxial modes stabilise closer to 1kHz. The attenuation of the different modes tends to increase with the frequency, especially the ground mode.

Bergeron models are tuned for one frequency, meaning that the propagation speed and attenuation of the different modes are correct for that frequency only, explaining the differences observed in Figure 2-Figure 5.

The model set to 50Hz and flat formation has a coaxial mode (the fastest mode) propagation velocity equal to 128m/μs, whereas the models set to 500Hz and 4800Hz have a coaxial mode speed equal to 168m/μs and 176m/μs, respectively. Thus, the wave of the 50Hz model requires more time to reach the receiving end of the cable, which also explains the lower frequency of the transient when tuning the model to 50Hz.

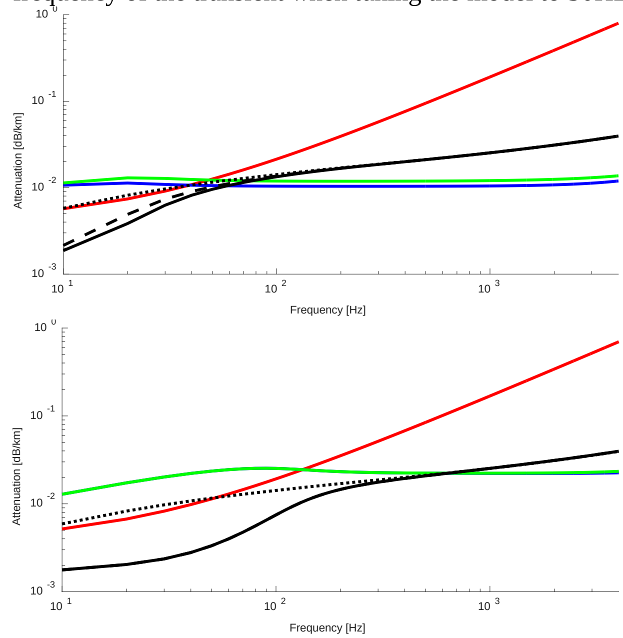

Figure 7 – Attenuation of the different modes in logarithm scale. Top: Flat formation; Bottom: Trefoil formation; Black: Coaxial modes; Green and blue: Intersheath modes; Red: Ground mode

The attenuation is also smaller the lower it is the target frequency of the model, resulting in a larger overvoltage for the 50Hz model. Additionally, as the attenuation does not stabilise after a threshold frequency the differences between the magnitudes of the 500Hz (green curve) and 4800Hz (blue curve) are more noticeable than the differences between the time instants when variations occur.

The dependency of the wave's speeds and attenuations in function of frequency explains the differences observed when the cable is modelled at both ends. However, the differences between models seem to be initially smaller when the cable is cross-bonded and such should be explained, before advancing more generic conclusions.

A major-section is typically divided into three minor-sections, with the screens transposed at the latter. At the end of each major section the screens are short-circuited and grounded, typically. Each transposition and/or grounding of the screens results in reflection and refraction of the waveforms for all modes; i.e., the coaxial mode waveforms are reflected and refracted, as are the intersheath and ground modes.

Moreover, the reflection/refraction of a modal waveform generates waveforms of other modes [4]. As an example, the coaxial mode waveforms reach the first transposition point earlier than the waveforms associated to intersheath and ground modes, but the refracted waves contain both coaxial and intersheath modes waves, with the latter being generated at the minor section. This new intersheath mode wave has the speed and attenuation alike the original one. Figure 8 shows the appearance of the intersheath modes at the first minor-section, because of the refraction of the coaxial modes; the magnitude of the coaxial modes also changes due to screen transposition.

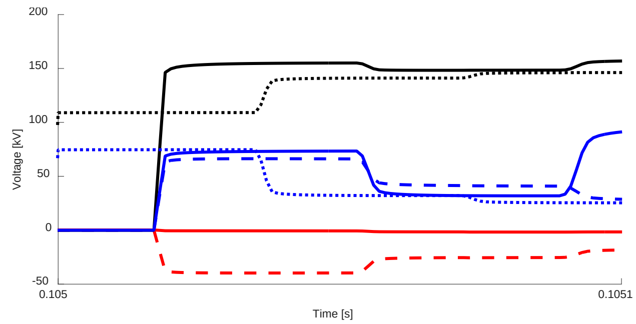

Figure 8 – Modal voltages: Dotted lines: Coaxial modes at sending end; Solid lines: Coaxial modes at 1st minor-section; Dashed lines: Intersheath modes at 1st minor-section

As a result, the transient waveforms of cross-bonded cables are not square as those of cables bonded at both-ends, but show many small variations, because of the reflections and refractions; the larger the number of major-sections the more noticeable this is. Consequently, the waveforms contain more frequencies, which may lead to a bigger inaccuracy of the Bergeron model, which is tuned for only one frequency. For the same reason, the time instant of the maximum peak voltage is no longer easily estimated. For a both-ends bonding, it corresponds to the moment that the coaxial modes arrive to the receiving end for the second time, i.e., after going back to the source/busbar and reflected at that point into the cable again, but that is not true for a cross-bonded cable, as it can be seen in Figure 9.

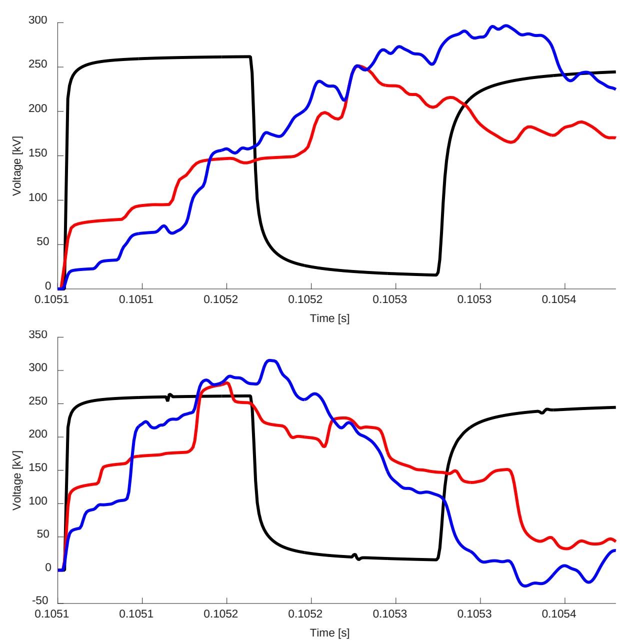

Figure 9 – Voltage at the end of the cable using FD-model. Top: Flat formation; Bottom: Trefoil formation. Black: Both-ends bonding; Red: 1 Major-section; Blue: Two major-sections

Having shortly explained the differences caused by the use of different bonding configuration, the differences between simulation models can be analysed.

The expectation is that the Bergeron model is more inaccurate for cross-bonded cables, because more frequencies are present and this is confirmed using Mean Absolute Error in section V. However, the error between models is smaller in the first instants of the transient; this happens because the voltage waveforms build up slower for cross-bonded cables (see Figure 9) and so, the error is less noticeable in the beginning.

The flat formation case (Figure 3) shows a very good agreement between the FD-models and the Bergeron models, except if the Bergeron is tuned to 50Hz, which is always inaccurate. The trefoil case (Figure 5) has more differences, with the 500Hz diverging sooner and the 4800Hz having a lower magnitude than the reference model, but it is still rather accurate. However, it is important to notice that differences depend on the cable layout, length or number of section. As an example, a small increase in the length of the minor sections would result in more noticeable differences for both formations.

The question is if guidelines can still be given in these conditions. As previously written, the transient waveform of a cross-bonded cable contains more frequencies. The velocity of the propagation modes stops changing at frequencies of some hundreds of Hertz and thus, one can say that the propagation speed is not much influenced by the changes in the bonding. The simulations plots concur with this conclusion and the 4800Hz tuned Bergeron model oscillations match those of the FD-model. However, the attenuation of the coaxial and ground models does not halt with frequency (Figure 7) and therefore, the reflection/refraction coefficients also do not halt. As a result, differences appear between the models.

One option for obtaining worse-cases could be to decrease the target frequency of the Bergeron model. The change in the propagation speed would be very small and the damping would decrease. Whereas this can be accomplished with relatively ease for cases where the target frequency is rather high and the wave propagation speed is stable, it may be unadvised for long cables with lower frequency transients.

An important aspect is that from an insulation coordination perspective, an engineer is often interested only on the first peak, which has the highest magnitude, normally. The difference in this peak is minor if the frequency is tuned, for both the time instant and the magnitude. This happens because the main differences between the models are caused by differences in the propagation speeds, attenuation and small differences in the reflection/refraction coefficients, which accumulate and are more visible with time. As a result, the first instants of transients are very similar for the different modelling approaches. Table 1 shows the magnitude of the first peak allowing verifying the previous statements, together with Figure 3 and Figure 5. Moreover, as it will be shown in the next section, the difference reduces with the modelling of the network around the cable being energised.

Table 1 – Magnitude of the first peak voltage and error, in percentage, to the reference model

	Flat	Trefoil
FD-model	251.3kV	281.5kV -
Bergeron – 4800Hz	253.0kV (0.7%)	271.9kV (3.4%)
Bergeron – 500Hz	258.8kV (3.0%)	269.3kV (4.3%)
Bergeron – 50Hz	263.3kV (4.8%)	267.1kV (5.1%)

IV. Network Modelling

The results presented in the previous section were for cables connected to ideal voltage sources. A realistic energisation, i.e., with the cable integrated in a grid, results in lower overvoltage and more complex waveforms, because of the propagation of the waves into the neighbour lines.

A variation of the previous case is prepared where the cable being energised is connected at the sending end to two other cables, which are in turn connected to an equivalent network at the other end. These two cables have different parameters, lengths of 7.26km and 12.51km and the system is in steady-state at the energisation instant. All three cable models are changed for the different simulations: the FD case has all three cables modelled with FD-models, the Bergeron at 4800Hz has all cables modelled with a Bergeron model tuned to 4800Hz and the same for the other Bergeron tuned frequencies. All cables have one major cross-bonded section.

It is important to refer that a larger portion of the network should have been modelled in order to have a more precise estimation of the peak voltage magnitudes and this simplified model will lead to higher transient peak voltages and the appearance of peak voltages that are not real after the first peak [4] (Figure 10 shows an example of this late peaks around 0.144 seconds, per example). This not completely accurate modelling approach is chosen to show that even in these conditions, the error associated to the Bergeron model is substantially smaller than when using an ideal voltage.

Figure 10 and Figure 11 show the voltage waveform at the end of the energised cable when using FD and Bergeron models tuned for different frequencies. Table 2 shows the magnitude of the first voltage peak for the different model approaches.

It is visible that the reference FD-model and 4800Hz-Bergeron waveforms are practically alike for almost the entire transient. This is mainly explained by two factors:

- The magnitude of the transient component injected into the cable is smaller and thus, the total error is also smaller;
- The waves that propagate into the neighbour lines are significantly damped when they arrive to the receiving end of the cable being energised; as a result, errors caused by the model are less noticeable;

A corollary of these two points is that the larger the modelled area, the smaller is the error of the Bergeron model, as the waves reflected at the neighbour cables have a smaller reflection coefficient. However, these reflections are irrelevant for the transients' waveforms after a certain modelling depth and it is useless to continue increasing the modelling depth. More information on network modelling for cable-based networks is available at [1] and [4].

Table 2 - Magnitude of the first peak voltage and error, in percentage, to the reference model

	Flat	Trefoil
FD-model	152.37kV	166.52kV
Bergeron – 4800Hz	151.16kV (-0.8%)	164.36kV (-1.3%)
Bergeron – 500Hz	153.18kV (0.5%)	170.56kV (2.4%)
Bergeron – 50Hz	170.56kV (12%)	168.81kV (1.4%)

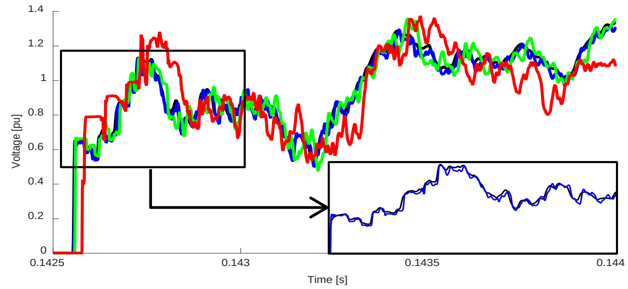

Figure 10 – Voltage at the end of the cable, with 1 major cross-section, flat installation and including network modelling, during energisation. Black: FD-model; Red: Bergeron at 50Hz; Green: Bergeron at 500Hz; Blue: Bergeron at 4800Hz

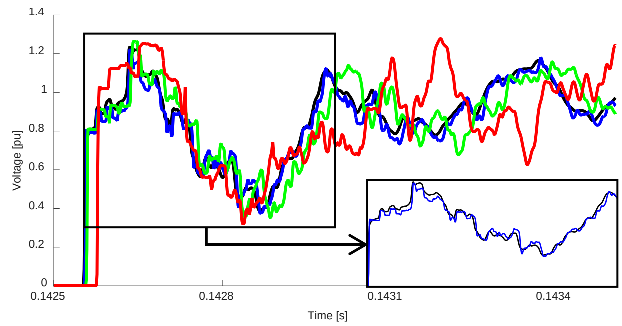

Figure 11 - Voltage at the end of the cable, with 1 major cross-section, trefoil installation and including network modelling, during energisation. Black: FD-model; Red: Bergeron at 50Hz; Green: Bergeron at 500Hz; Blue: Bergeron at 4800Hz

V. Mean Absolute Error

The comparisons previously performed were partially based in visual comparison to ease the understanding of the results. This section will quantify the error of the different modelling approaches confirming the explanations previously provided.

Figure 12-Figure 14 show the mean absolute error of the different Bergeron models, when compared with the FD-models, for the cases previously shown, plus the results for the cable with two major cross-bonded sections and connected to an ideal voltage source. The error is accumulated, meaning that the value at 1ms is the mean absolute error between 0s and 1ms, whereas the value at 2ms is the mean absolute error between 0s and 2ms. The errors are calculated for per units. The results are for trefoil formation with those for flat formation showing the same behaviour, but smaller errors.

The mean absolute error confirms the previous explanations. The error is approximately two times smaller for the 4800Hz-Bergeron, when compared with the 500Hz-Bergeron and the error of the 50Hz models is quite high. As expected the error when modelling the neighbour network is considerably smaller: it is always inferior to 0.04pu for the 4800Hz-Bergeron, except for the first 0.2ms, when it is between 0.04pu and 0.05pu.

It can be argued that from an application perspective, the values of the errors are a little misleading and can be considered smaller than in the figures. Transient waveforms are characterised by fast changes with high derivatives. The small differences in the propagation velocities of the different models cause that these variations do not occur at precisely the same instant, with differences in the order of micro-seconds. These μs differences cause an increase of the error, because of the differences between magnitudes, which reflect in the mean absolute error during the first instants; as an example, for the system with network modelling, the Bergeron-4800Hz has at around 76μs a difference to the FD-model of approximately 0.12pu that lasts 4μs. For insulation coordination this difference is not so important, as one is more interested in the magnitude of the overvoltage and the respective duration.

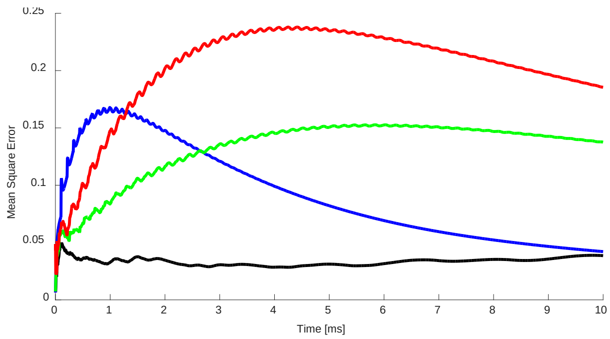

Figure 12 – Mean Absolute Error when using Bergeron tuned for 4800Hz. Black: Network modelling; Blue: Voltage Source and both-ends bonding; Green: Voltage Source and 1 major-section; Red: Voltage-source and 2 major-sections

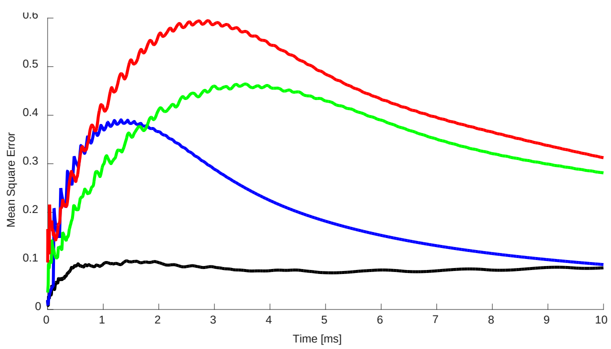

Figure 13 – Mean Absolute Error when using Bergeron tuned for 500Hz. Black: Network modelling; Blue: Voltage Source and both-ends bonding; Green: Voltage Source and 1 major-section; Red: Voltage-source and 2 major-sections

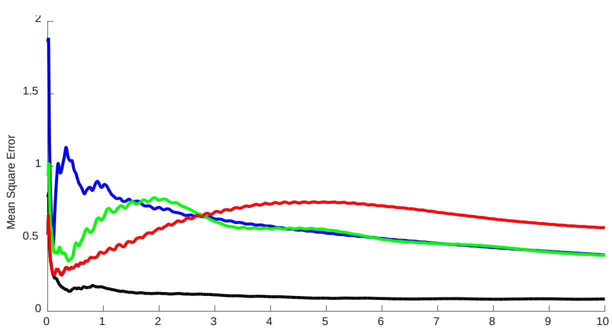

Figure 14 – Mean Absolute Error when using Bergeron tuned for 50Hz. Black: Network modelling; Blue: Voltage Source and both-ends bonding; Green: Voltage Source and 1 major-section; Red: Voltage-source and 2 major-sections

VI. CONCLUSIONS

This paper tried to compare the error associated to the use of Bergeron models for the simulations of switching transients in cables against a reference FD-model. It is shown that the error is small if the Bergeron model is tuned for the transient's main frequency and the network around the cable is modelled, a condition required for accurate results, independently of the chosen model.

Inaccuracy in the calculations of the transient's main frequency increases the error, but not much, unless if the frequencies become small; as an example, the error of the model tuned to 500Hz is twice the error of the model tuned to 4800Hz. This happens, because the propagation speed of the different modes is virtually stable for frequencies over some hundreds of Hz. The attenuation of the different modes does not halt, but the variation is smaller as the frequency increases; these are typical results, which will have variations depending on the cable geometry.

The simulation for cross-bonded cables will show a bigger error than if the cable was bonded at both-ends, because more frequencies are present during a transient for the former. However, the error of latter is larger in the first instants, because the voltage magnitudes are also larger and thus, the error is more noticeable in absolute values.

The conclusions were backed by a theoretical analysis based on modal theory and an agreement was found between the theoretical expectations and the results, reinforcing the conclusions obtained in the paper.

Future work will expand this analysis to transients originated by lightning in hybrid OHL-cable lines and overvoltage due to temporary resonances caused by the energisation of a cable.

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